Configuration Strategies of Reactive Power Compensation in Converter Stations with STATCOM

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Abstract. Installing static synchronous compensators (STATCOM) is one of the key methods to mitigate the issues of voltage fluctuation in converter stations connected to weak AC systems. This paper introduces an optimised mathematical model which provides the configuration strategies of reactive power compensation and determines the optimal size of capacitor banks in the receiving converter station with STATCOM installed. The model also considers the steady-state operation conditions of AC-DC systems, and both steady-state and transient reactive power characteristics of STATCOM. A case study is used to verify the model, which considers a back-to-back interconnection project located at the southern region of China. The case study successfully proves the adaptability and rationality of the model, demonstrating it is suitable to be used for reactive power compensation strategies of receiving converter station projects during preliminary studies.

Keywords: Converter station · HVDC · Reactive power compensation · STATCOM

1 Introduction

Reactive power compensation of converter stations is one of the key aspects during the preliminary study and design stages of conventional HVDC power transmission and transformation projects. The reactive power compensation strategies need to consider the overall reactive power balance and sizes of capacitor banks. In a weak AC system, switching operations of capacitors or filters often cause excessive voltage fluctuations (both steady- and transient-states) at AC busbars; this is due to the low short-circuit capacity at the coupling point, resulting in insufficient voltage support capability provided by the system. To ensure that the voltage fluctuation is within the acceptable range, a common method is to reduce the rated capacity of individual capacitor banks. However, reducing rated capacity requires higher total numbers of capacitor banks to be deployed, which means larger site spaces and potentially increasing investment [1].

Dynamic reactive power compensation devices have been widely used in correcting power factors at AC side, preventing commutation failure at DC side, and connecting non-hydro renewable energy resources [2–7]. Authors in [8] have introduced the installation

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of Static Var Compensators (SVCs) at 500 kV back-to-back grid interconnection project between China and Russia to increase the rated capacity of AC filter/capacitor capacity, ensure the steady-state stability at the China side, and improve the transient stability at Russia side. Paper [9] proposes a multi-mode coordinated control strategy based on STATCOM and capacitor banks, and demonstrates the feasibility of the proposed method on the Jiuquan to Hunan ultra-high voltage direct current (UHVDC) transmission system. Paper [10] studies the operation characteristics and improvement measures of the DC transmission systems connected with weak AC grids; the authors propose to install STATCOM at the Funing converter station and add series compensation devices at the AC outgoing busbars to enhance the dynamic reactive power adjustment abilities of the AC grids in the neighbouring area of the receiving end.

Currently, the maximum capacity of individual capacitor banks in conventional DC converter stations is determined using commercial power system simulation software during preliminary research stages. However, the process requires a large amount of calculation and lacks efficiency. It becomes even more complicated with STATCOM (or other compensation methods) taken into consideration. This paper addresses the aforementioned issue by proposing a novel configuration strategy of reactive power compensation in converter stations equipped with STATCOM. The paper is organised as follows. The operation principle of AC-DC system is analysed in Sect. 1; then detailed reactive power transient stability of STATCOM is discussed in Sect. 2; after that, an optimisation model for calculating the maximum capacity of capacitor banks after installing STATCOM is proposed in Sect. 3; finally, the model is verified and validated in PSD-BPA software in Sect. 4.

2 Equivalent Circuit of AC-DC Systems

The steady-state equivalent model of a simplified AC-DC system is shown in Fig. 1.

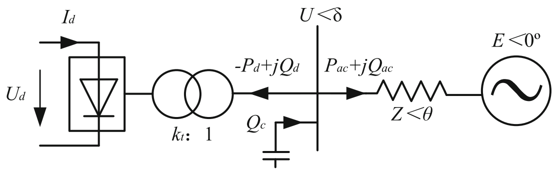

Fig. 1. The steady-state equivalent model of a AC-DC system [11]

The operating characteristics of the AC-DC system are described using (1)–(4):

$$P_{ac} = \frac{1}{|Z|}\left[U^2\cos\theta - EU\cos(\theta + \delta)\right] \tag{1}$$

$$Q_{ac} = \frac{1}{|Z|}\left[U^2\sin\theta - EU\sin(\theta + \delta)\right] \tag{2}$$

$$P_d - P_{ac} = 0 \tag{3}$$

$$Q_d + Q_{ac} - Q_c = 0 \tag{4}$$

where P_{ac} and Q_{ac} are the active and reactive power exchange between the AC grid and the receiving converter station, respectively; E is the voltage magnitude of the equivalent AC system at the receiving end; U and δ are bus voltage magnitude and phase angle of the receiving end of the inverter; Z and θ are the magnitude of Thevenin equivalent impedance and phase angle of the receiving end, respectively; P_d and Q_d are the active power and reactive power output from the converter station, respectively; Q_c is the reactive power provided by the compensation devices.

Based on the control methods commonly used in DC systems, the active and reactive power corresponding to the DC side can be represented at the coupling bus of the AC-DC system [12].

Constant current control mode at rectifier and constant voltage control mode inverter side are expressed in (5) and (6).

$$P_d = U_d I_d \tag{5}$$

$$Q_{ac} = \sqrt{\left(\frac{3\sqrt{2}}{\pi}k_t U I_d\right)^2 - P_d^2} - Q_c \tag{6}$$

where k_t is the turns ratio of the converter transformer; U_d and I_d are the voltage and current at DC side, respectively (both of them are constant values).

2) Constant current control mode at rectifier side and constant arc extinguishing angle control (Amax) mode at inverter side are expressed in (7) and (8).

$$P_d = \left(\frac{3\sqrt{2}}{\pi}k_t U cos r_s - \frac{3}{\pi}kX_c I_d\right)I_d \tag{7}$$

$$Q_{ac} = \sqrt{\left(\frac{3\sqrt{2}}{\pi}k_t U I_d\right)^2 - P_d^2} - Q_c \tag{8}$$

where r_s is the arc extinguishing angle of the inverter, r_s and I_d are constant values; X_c is the leakage reactance of the converter transformer.

3 Equivalent Model of STATCOM

3.1 Steady-State Characteristics

STATCOM realises reactive power exchange with the AC systems by adjusting the magnitude and phase angle of the output voltage. The system is capable of providing fast responses and leading/lagging symmetrical reactive current to effectively adjust the reactive power, balance three-phase voltage, and maintain suitable static or dynamic voltage variation. The mathematical expression of STATCOM in steady-state [13] in shown in (9) and (10).

$$V = V_{REF} + X_{SL} I_S \tag{9}$$

$$Q_S = VI_S \tag{10}$$

where V is the output voltage of STATCOM; V_{REF} is the reference voltage of the controlled busbar; X_{SL} is the droop reactance; I_S is the terminal current; Q_s is the reactive power output. The steady-state voltage-current (V-I) characteristics of STATCOM are shown in Fig. 2.

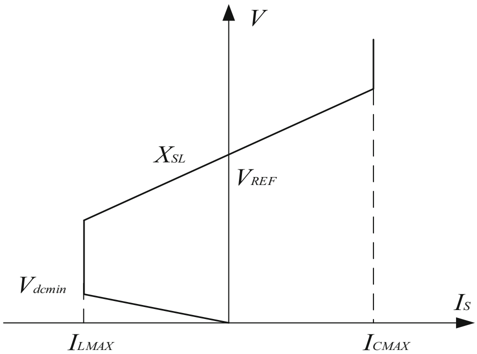

Fig. 2. Steady-state V-I characteristics of STATCOM.

When STATCOM is operating at an adjustable state, the reactive power output can be expressed as (11) and (12).

$$Q_S = VI_S = V\frac{V - V_{REF}}{X_{SL}} \tag{11}$$

$$I_{Lmax} \leq I_S \leq I_{Cmax} \tag{12}$$

where I_{Lmax} and I_{Cmax} are the maximum inductive output current and the maximum capacitive output current, respectively.

3.2 Transient Characteristics

The transient characteristic analysis of STATCOM is based on the model presented in [14], and the detailed schematic control diagram is illustrated in Fig. 3:

A series of simulation studies have been carried out to investigate the reactive output characteristics based on either various STATCOM sizes under fixed reactive (capacitive) power shedding (as shown in Fig. 4) or fixed STATCOM size under various reactive (capacitive) power shedding (as shown in Fig. 5).

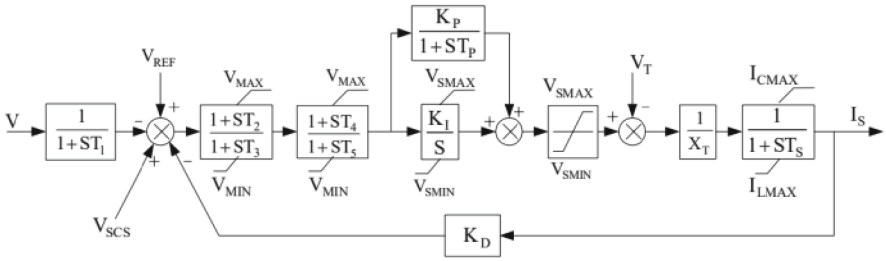

Fig. 3. Control diagram of STATCOM.

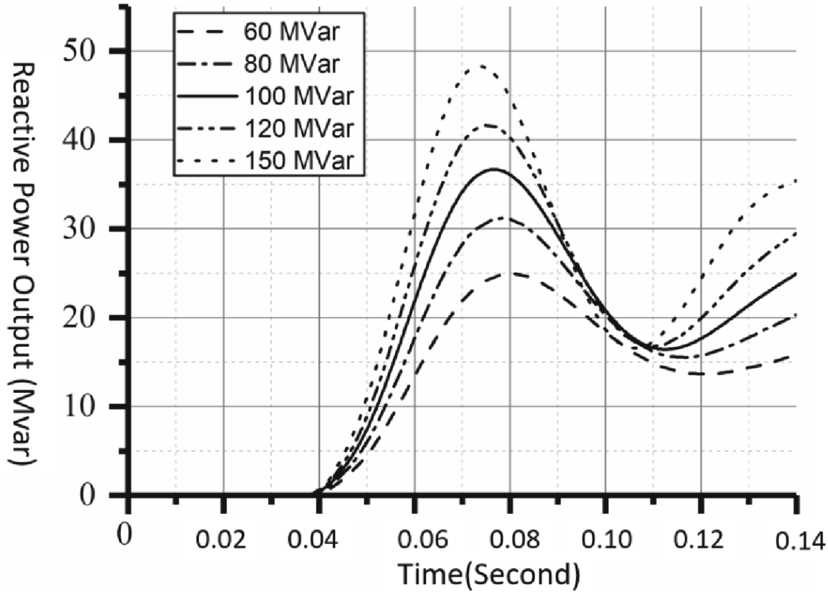

Fig. 4. STATCOM reactive power output with different capacities under fixed reactive power shedding.

The simulation results show the maximum reactive power output of STATCOM during the transient process has a positive correlation with the installed capacity and amount of reactive power shedding. The maximum transient reactive power output and steady-state reactive power output are summarised in Table 1.

To reflect the effectiveness of STATCOM in terms of managing transient voltage fluctuations, linear fitting is used to obtain the approximate relationship between maximum transient reactive power output and steady-state output of STATCOM when a single capacitor bank is removed:

$$Q_S^{'} = AIQ_S + B \tag{13}$$

$$Q_S^{'} \leq Q_{Smax}^{'} \tag{14}$$

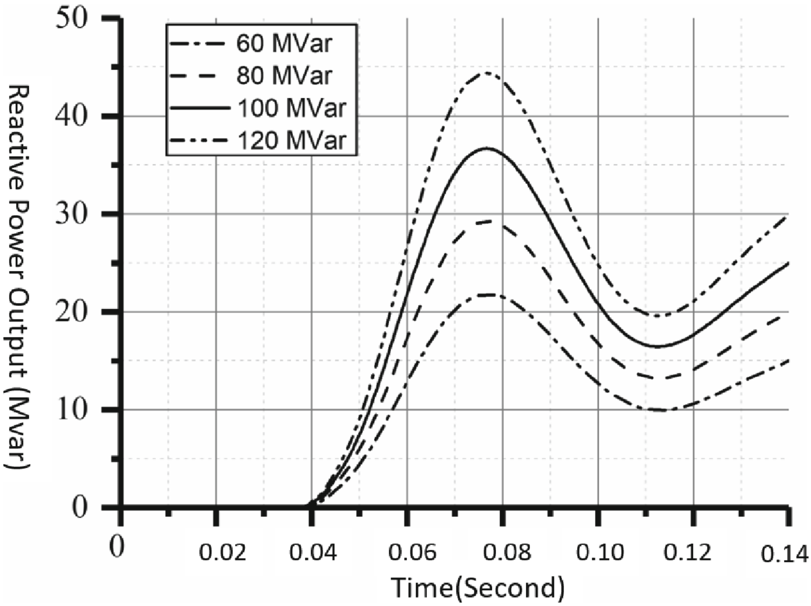

Fig. 5. STATCOM reactive power output with fixed capacity under different reactive power shedding.

where A and B are determined by the capacity of STATCOM and the removal of capacitor banks, and Q'_{Smax} is the maximum transient reactive power output of STATCOM.

4 Reactive Power Compensation Strategy for Converter Stations

The reactive power consumed by the converter station is affected by the active power, DC voltage, DC current, firing angle and extinction angle. The capacity reactive power compensation devices that need to be installed in the converter station can be calculated using Eq. (15) according to.

$$Q_{total} \geq \frac{Q_{ac} + Q_{dc}}{U^2} + NQ_{sb} \tag{15}$$

where Qtotal is the total reactive power provided by the reactive power compensation device under normal voltage; Qsb is the reactive power provided by the largest AC filter combination or shunt capacitor banks under normal voltage; N is the number of standby compensation devices (normally N = 1); Qdc is the reactive power loss of converter station; Qac is the reactive power exchange between the converter station and the AC system, in which the compensation provided by AC systems is not considered in this study.

If the total capacity is fixed, the capacity of a single bank and the number of banks will be the main factors that affect the overall investment and land occupation. The capacity of individual banks is restraint by AC busbar transient voltage fluctuation during capacitor

Table 1. Comparison of maximum transient reactive power output and steady-state reactive power output of STATCOM.

STATCOM capacity (Mvar)	Reactive power shedding (Mvar)	Maximum transient output reactive power (Mvar)	Steady-state output reactive power (Mvar)
2 × 100	150	57.5	41.2
	130	49.5	35.8
	110	41.6	30.3
	90	33.9	24.6
	70	26.3	19.1
2 × 120	150	65.9	45.2
	130	56.1	39
	110	46.9	32.8
	90	37.9	26.8
	70	29.3	20.7
2 × 150	150	79	49.4
	130	67.3	42.7
	110	56.1	35.9
	90	45.3	29.5
	70	34.8	22.8

bank switching. Such transient voltage fluctuation shall not be greater than 2%, the steady-state voltage fluctuation shall not be greater than 1%, and the rate of change of transient voltage caused by switching shall not be greater than 6% as defined by the national standard GB/T 31460-2015 "Technical Guide for Reactive Power Compensation and Allocation of HVDC Converter Station".

A mathematical model is proposed as follows to optimise the rated capacity of individual capacitor banks at the receiving-end converter station fitted with STATCOM under a weak AC system.

4.1 Constant Current Control Mode at Rectifier Side or Constant Voltage Control Mode at Inverter Side

$$\max \Delta Q = Q_1 - Q_2 \tag{16}$$

s.t.

$$P_d - \frac{1}{|Z|}\left[U_1^2 \cos\theta - EU_1 \cos(\theta + \delta_1)\right] = 0 \tag{17}$$

$$\sqrt{\left(\frac{3\sqrt{2}}{\pi} k_t U_1 I_d\right)^2 - P_d^2} - Q_1 - \frac{1}{|Z|}\left[U_1^2 \sin\theta - EU_1 \sin(\theta + \delta_1)\right] = 0 \tag{18}$$

$$P_d - \frac{1}{|Z|}\left[U_2^2\cos\theta - EU_2\cos(\theta + \delta_2)\right] = 0 \quad (19)$$

$$\sqrt{\left(\frac{3\sqrt{2}}{\pi}k_t U_2 I_d\right)^2 - P_d^2} - Q_2 - Q_S - \frac{1}{|Z|}\left[U_2^2\sin\theta - EU_2\sin(\theta + \delta_2)\right] = 0 \quad (20)$$

$$\frac{U_1 - U_2}{U_1} \le 1\% \quad (21)$$

$$\frac{Q_1 - Q_2 - Q_S^{'}}{S_d} \le 2\% \quad (22)$$

$$Q_S^{'} \le Q_{smax}^{'} \quad (23)$$

4.2 Constant Current Control Mode at Rectifier Side or Constant Arc Extinguishing Angle Control Mode at Inverter Side

When the inverter side adopts the constant arc extinguishing angle control method, Eqs. (17) and (19) in the optimisation model can be replaced with Eqs. (24) and (25), and the objective function and rest of constraints conditions remain the same.

$$\left(\frac{3\sqrt{2}}{\pi}k_t U_1 cosr_s - \frac{3}{\pi}X_c I_d\right)I_d - \frac{1}{|Z|}\left[U_1^2\cos\theta - EU_1\cos(\theta + \delta_1)\right] = 0 \quad (24)$$

$$\left(\frac{3\sqrt{2}}{\pi}k_t U_2 cosr_s - \frac{3}{\pi}X_c I_d\right)I_d - \frac{1}{|Z|}\left[U_2^2\cos\theta - EU_2\cos(\theta + \delta_2)\right] = 0 \quad (25)$$

Using the proposed model, the maximum capacity of individual bank under each control mode can be obtained respectively. The capacitor grouping strategy is finally determined based on several factors, including the need for total reactive power demand in (15), converter station wiring, rate of change of transient voltage regulation caused by switching of reactive power compensation devices, and land occupation.

5 Case Analysis

A back-to-back interconnection project in the southern region of China is used as a case study to verify the applicability and rationality of the model. Two back-to-back conventional DC units with a total capacity of 2 × 1000 MW is planned to be installed in the converter station. The rated DC voltage is ±100 kV, and rated operating current is 5000 A. Both sides of the converter station are connected with double 500 kV lines. The length of the one line (west side) is around 130 km. In the case of line N-1 contingency situation, the DC short-circuit ratio is 2.3, which is categorised as a weak AC system connection. It is therefore considered to install a STATCOM device on the west side of the converter station to suppress the switching voltage fluctuation when filters are switched onto the system, and ensure the system stability and security during N-1 contingencies.

According to the DC design parameters of the back-to-back converter station, when the west side of the station is operated as receiving end, the required reactive power compensation under constant voltage control mode is approximately 1150 Mvar. Combined with the relevant parameters of the AC system, an optimisation model of the capacitor banks is established. The calculated results are compared with PSD-BPA simulation software. The result comparison is summarised in Table 2.

Table 2. Comparison of reactive groups under the control mode of terminal constant voltage

	Calculated results (Mvar)	Steady-state voltage fluctuation (%)	BPA simulation results (Mvar)	Steady-state voltage fluctuation (%)	Deviation
Without STATCOM	76	0.85	80	1	5.0%
2 × 150 Mvar STATCOM	145	0.88	150	0.99	3.3%
2 × 120 Mvar STATCOM	130	0.87	135	1	3.7%

The results show that the constraint factor of the rating of a single capacitor bank is dominated by the 1% voltage fluctuation requirement in steady-state when STATCOM is considered. The deviation between the proposed model and BPA ranges from 3.3% to 5% in all scenarios, which satisfies the requirement of feasibility studies during the preliminary stages.

Based on two kinds of STATCOM capacities, two reactive power configuration schemes are proposed as follows.

- Option 1: Install 2 × 150 Mvar STATCOM and 3 large groups, each large group consists of 8 small groups with capacity of 145 Mvar;
- Option 2: Install 2 × 120 Mvar STATCOM and 3 large groups, each large group consists of 9 small groups with capacity of 130 Mvar.

The transient voltage fluctuation when large capacitor groups are being switched on is verified in the end. Analysis shows the transient voltage fluctuations of both options are 6.3% and 5.6%, respectively. Option 1 exceeds 6% voltage fluctuation limit specified in the standard, so the grouping scheme needs to be adjusted. Whereas, option 2 meets the operation requirements, and is suitable to be applied. This case study demonstrates the proposed model can be used as a preliminary analysis method to quickly select STATCOM and configuration of reactive power compensation devices, which greatly enhances the computing efficiency.

6 Conclusion

Having analysed the steady-state operation principle of AC-DC system and the transient steady-state model of STATCOM, this paper introduces two typical control methods for constant current control at rectifier side/constant voltage control at inverter side, and constant current control at rectifier side/constant arc extinguishing angle at inverter side. In addition, the mathematical model which helps optimise the rating of reactive power compensation devices is proposed. Finally, the calculation results of the model are compared with commercial simulation tools based on an interconnection project in the real world. The studies have shown the model is capable of quickly selecting STATCOM and configuration strategies of reactive power compensation.

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